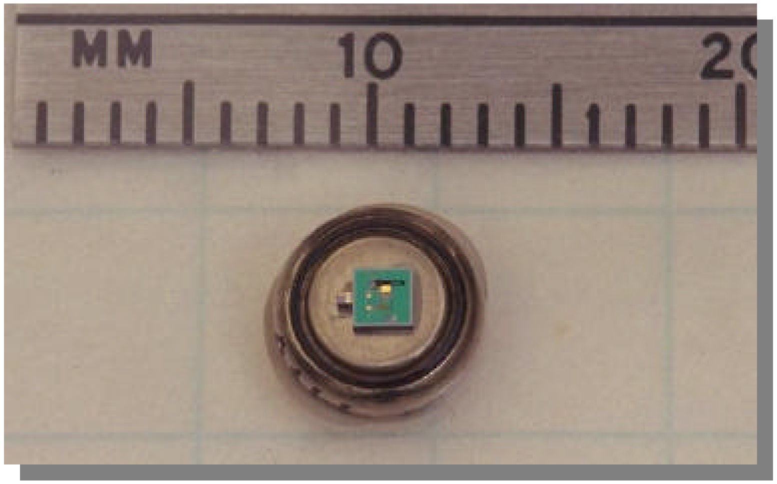
Berkeley Sensor & Actuator Center

Preliminary Smart Dust Mote



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University of California, Berkeley

HOT CHIPS 12
A Symposium on High-Performance Chips at Stanford University
August 13-15, 2000

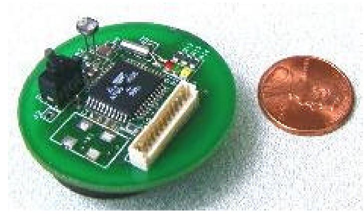
BSAC

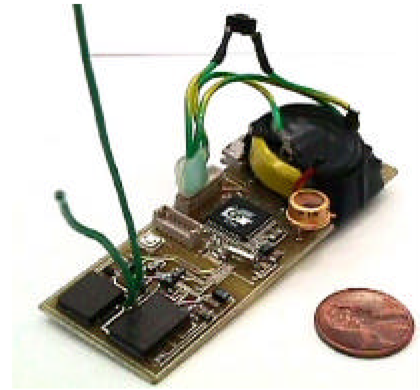
Smart Dust
Goals

- Autonomous sensor node (mote) in 1 mm^3
- Thousands of motes
- Many interrogators
- MAV delivery

- Demonstrate useful/complex integration in 1 mm^3

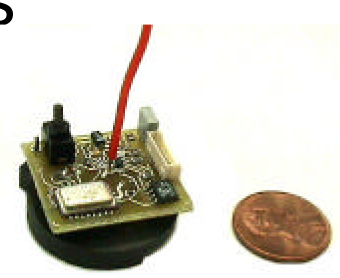
COTS Dust

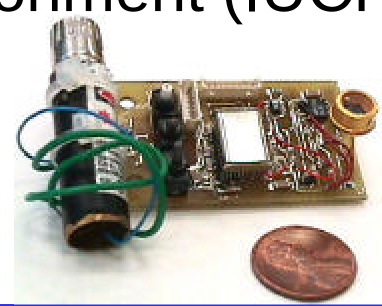


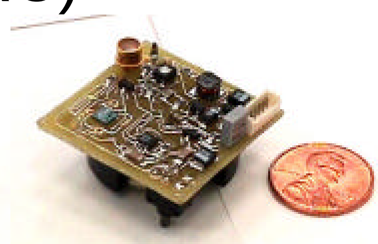


GOAL:
- Get our feet wet

RESULT:
- Cheap, easy, off-the-shelf RF systems
- Fantastic interest in cheap, easy, RF:
  - Industry
  - Berkeley Wireless Research Center
  - Center for the Built Environment (IUCRC)
  - PC Enabled Toys (Intel)
  - Endeavor Project (UCB)
- Optical proof of concept



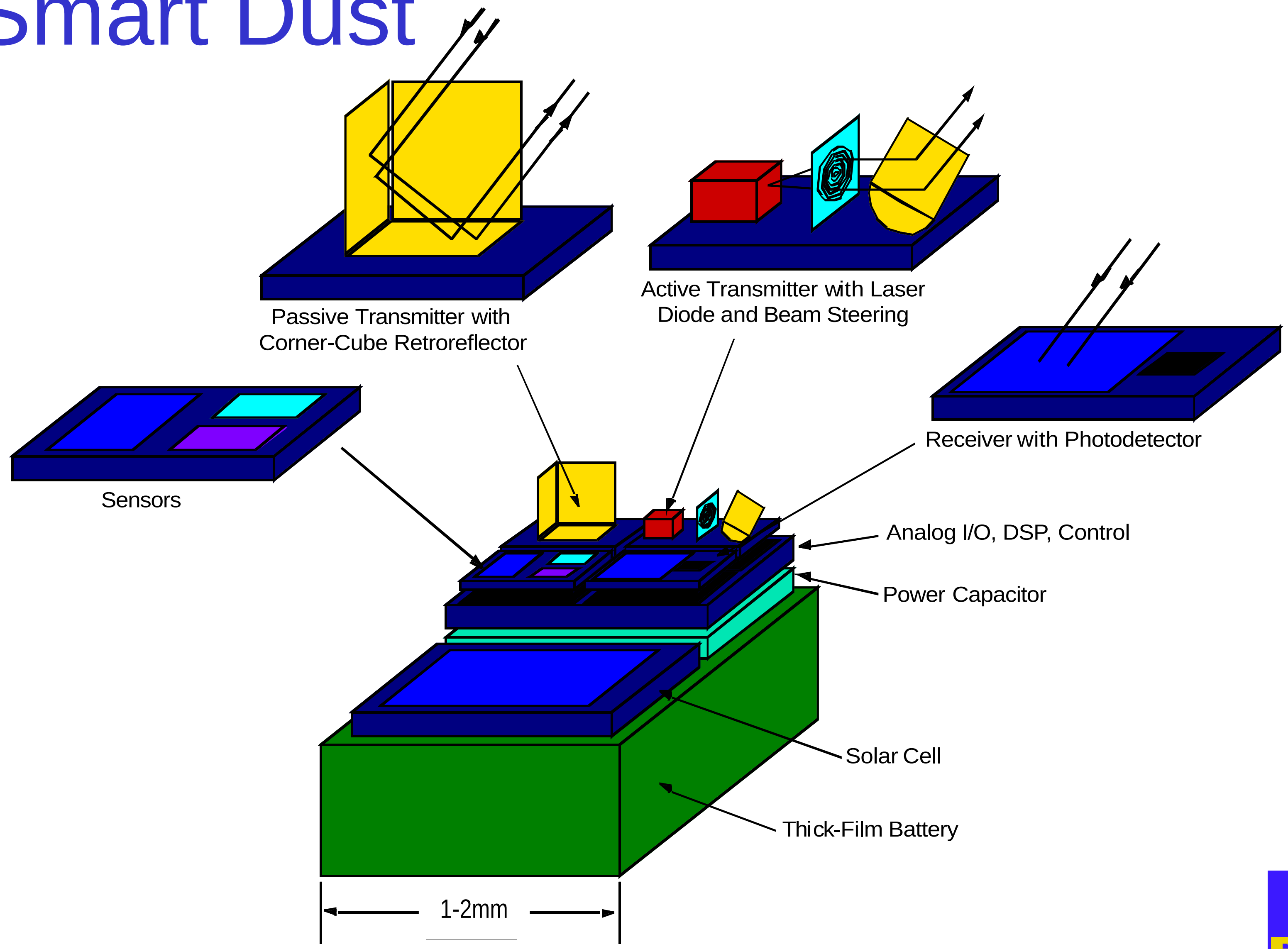




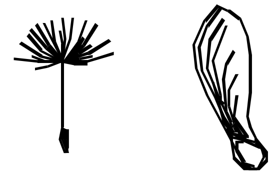
Power and Energy

- Storage
  - Batteries ~1 J/mm^3
  - Capacitors ~10 mJ/mm^3
- Sources
  - Solar cells
    - Full sun: ~0.1mW/mm^2, ~1J/day/mm^2
    - Indoor: 0.1-10µW/ mm^2, 1-100mJ/mm^2
  - Combustion/Thermopiles
- Energy Consumption
  - Digital control: ~1nJ/instruction (StrongARM SA1100)
  - Analog circuitry: ~1nJ/sample
  - Communication: ~1nJ/bit (passive transmitter)

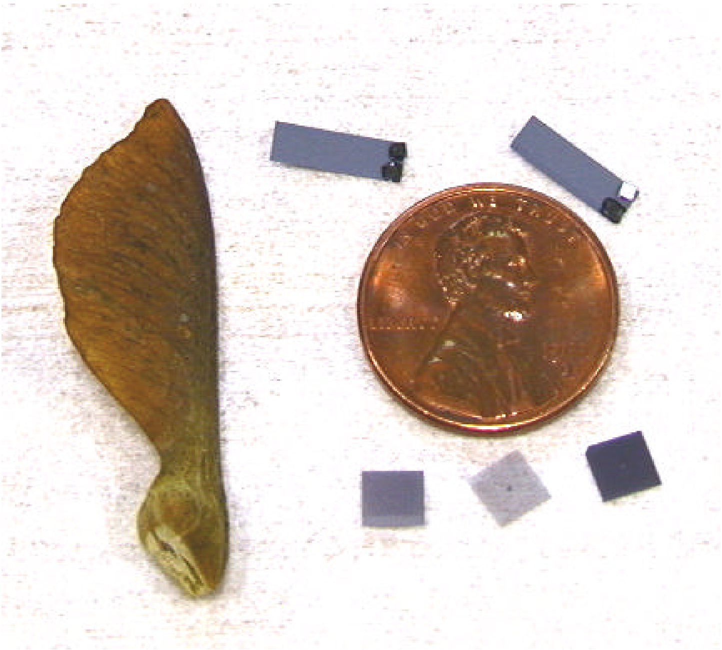
Smart Dust

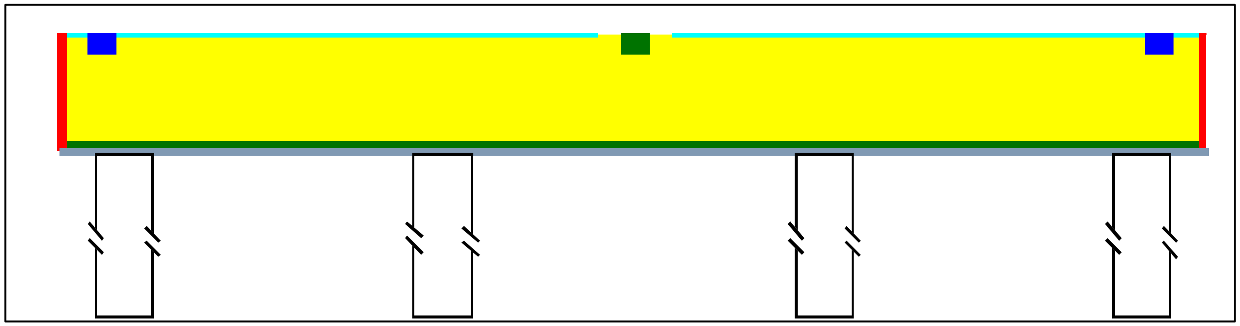

Passive Transmitter with
Corner-Cube Retroreflector
Active Transmitter with Laser
Diode and Beam Steering
Receiver with Photodetector
Sensors
Analog I/O, DSP, Control
Power Capacitor
Solar Cell
Thick-Film Battery
1-2mm

Solar Power



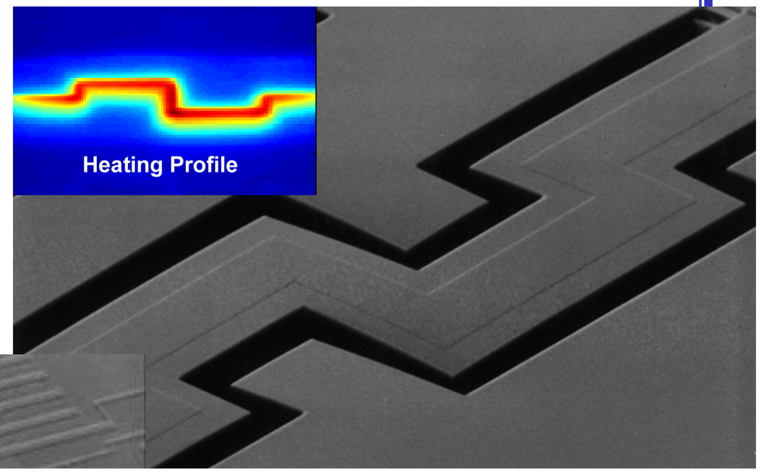
- Silicon maple seeds
- Silicon dandelion seeds
- Currently 3% efficient
  - Sunlight: 26µW/mm^2
  - Fluorescent room light: 0.21 µW/mm^2

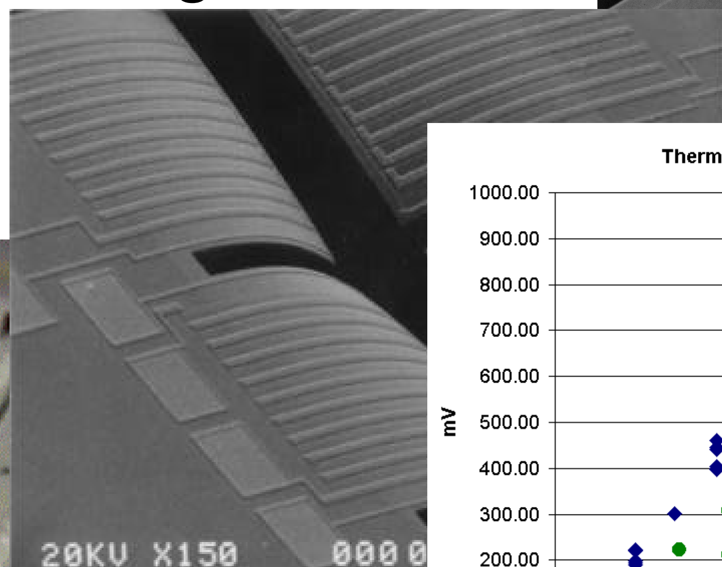


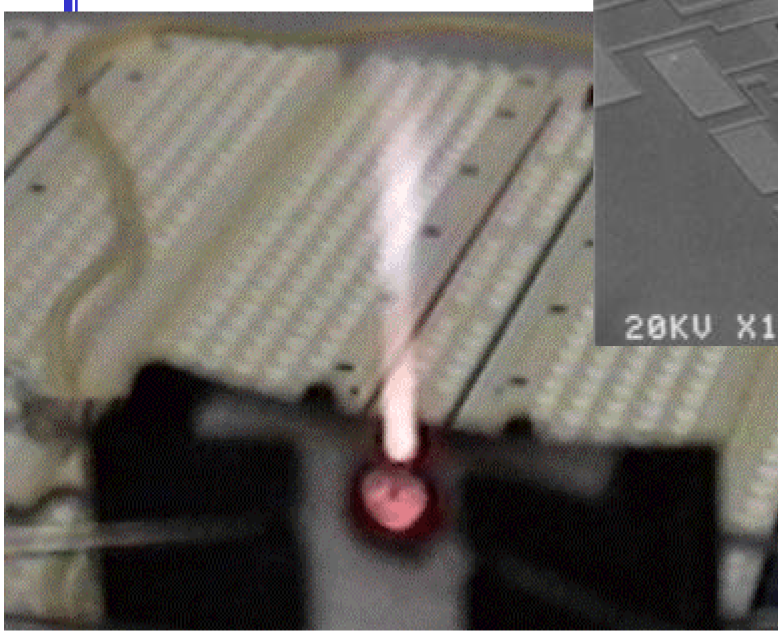


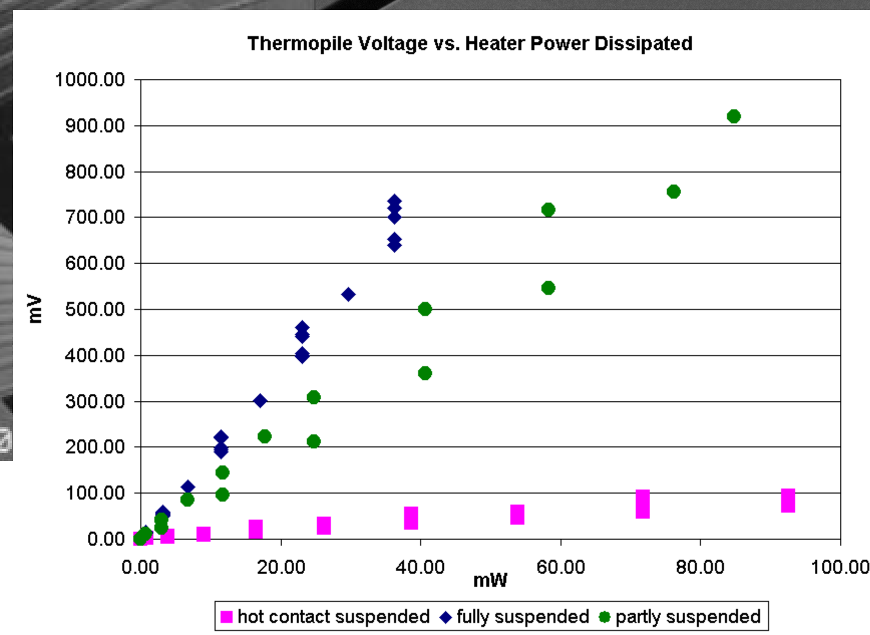
Combustion

- Solid rocket propellant
- Integrated igniter
- Thermoelectric generator



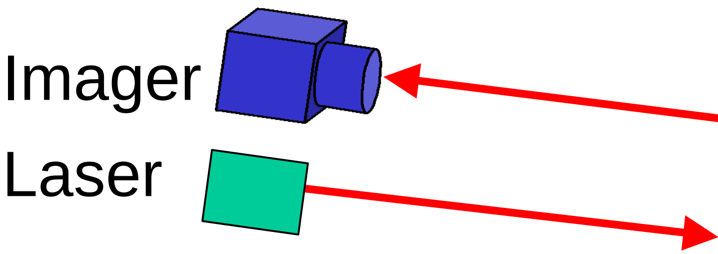


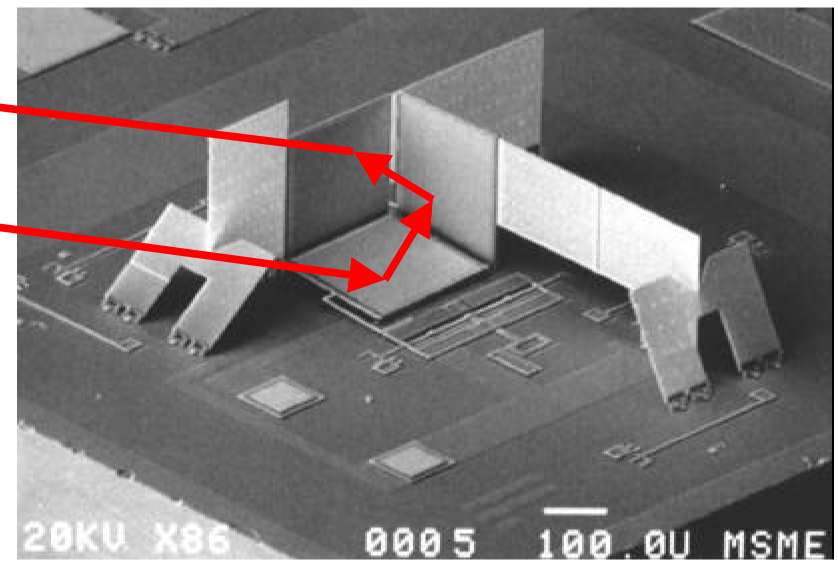




Optical Communication

Corner Cube Reflector (CCR)





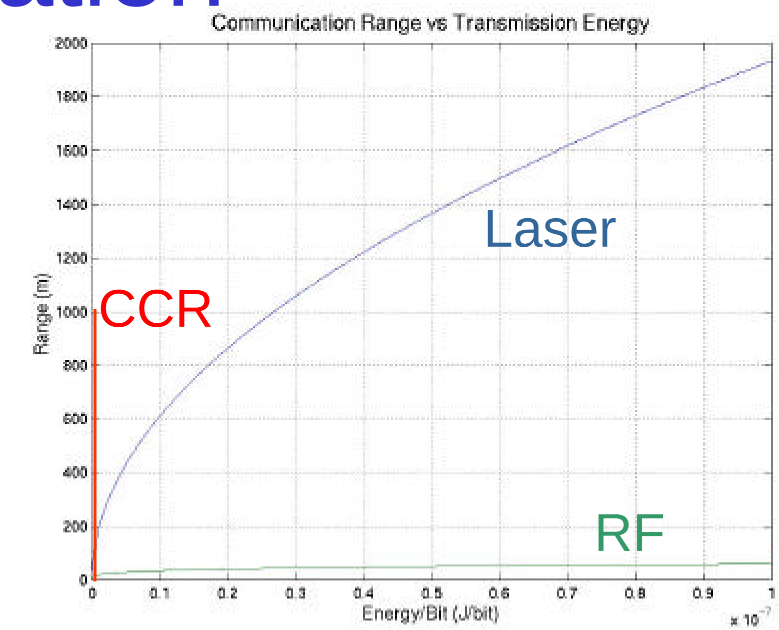
Courtesy of Victor Hsu

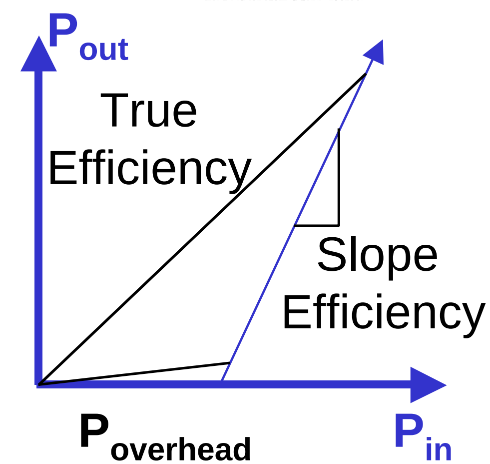
- Capacitive actuation
- 150m demonstrated range
- 118bps with 8V actuation
- 670 pJ/bit

Optical Communication

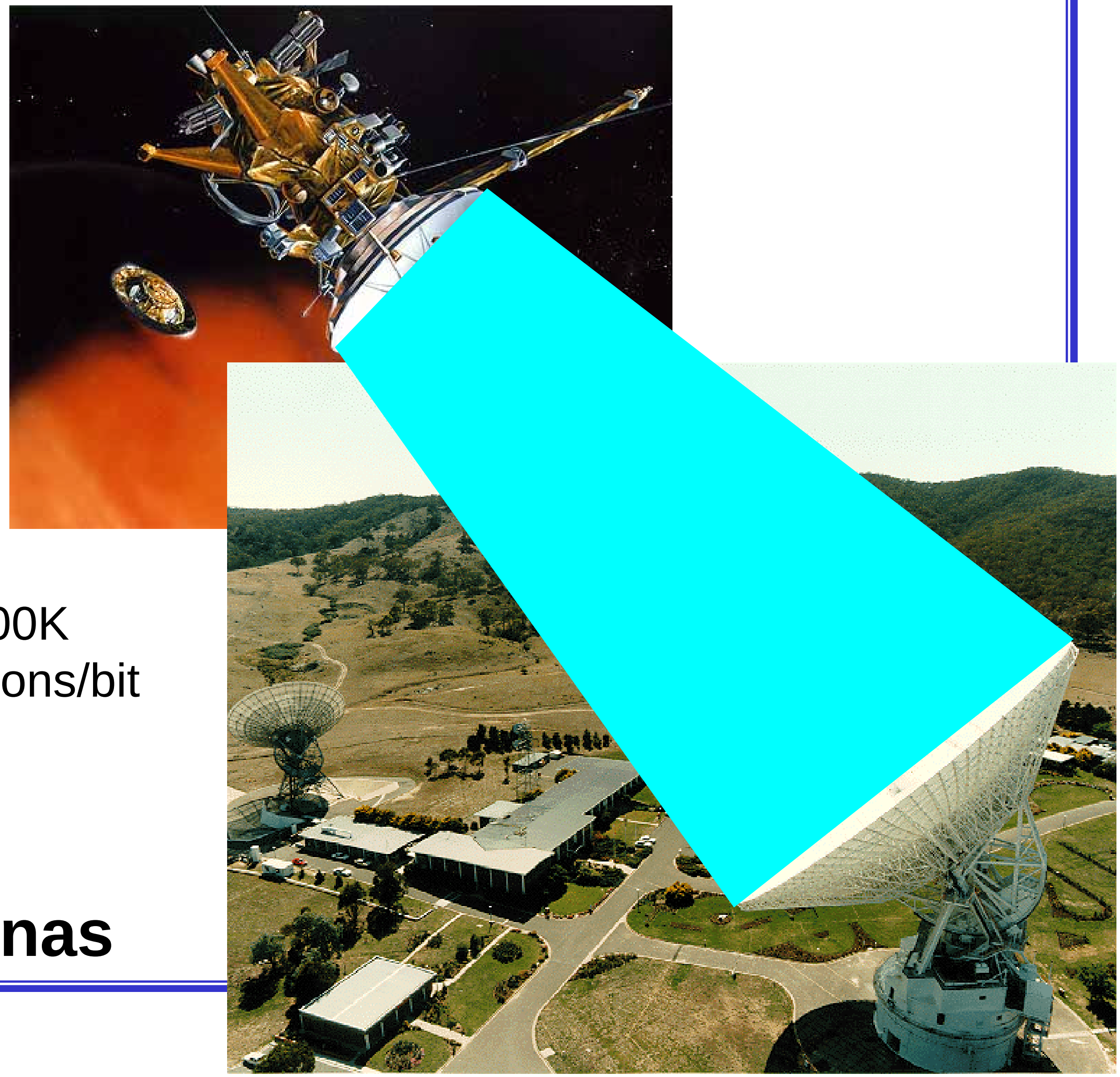
Advantages

- Large antenna gain
- Small radiator
- Spatial division multiple access (SDMA)
- Received power $\propto 1/d^2$
  - RF received power $\propto 1/d^{2\rightarrow 7}$
- Output efficiency
  - Optical
    - Laser slope efficiency
    - $P_{overhead}$ = 1uW-100mW
  - RF
    - GMSK slope efficiency ~50%
    - $P_{overhead}$ = 1-100mW





Limits to RF Communication



Cassini

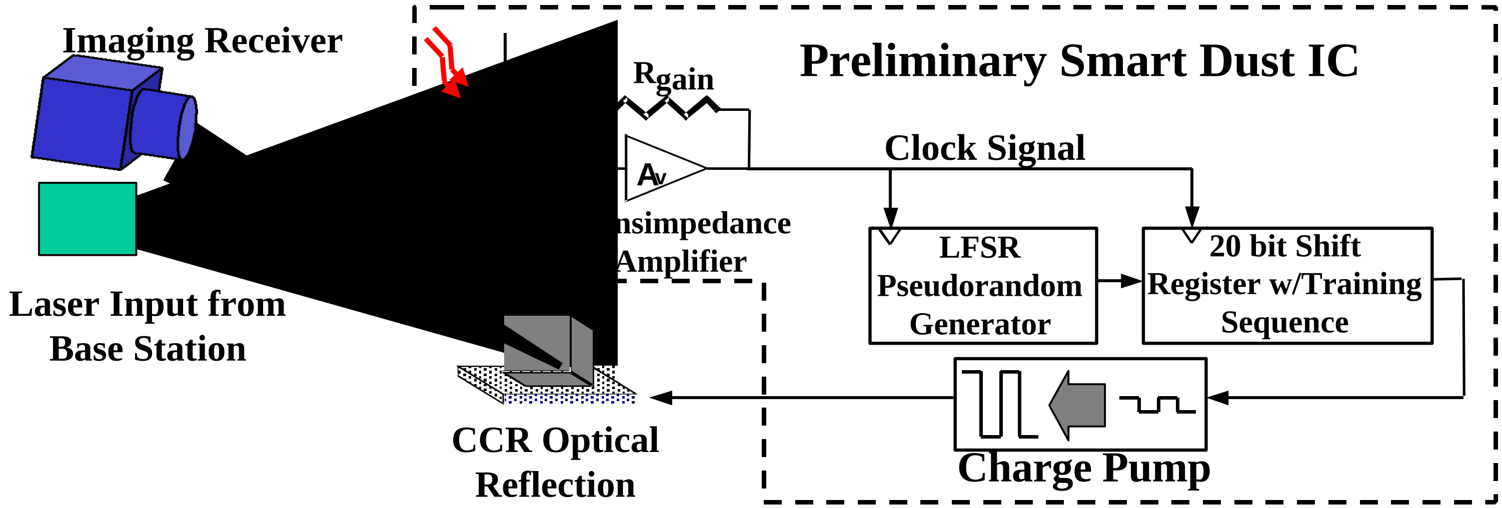
- 8 GHz (3.5cm)
- 20 W
- 1.5×10^9 km
- 115 kbps
- -130dbm Rx
- 10^{-21} J/bit
  - kT=4x 10^{-21} J @300K
  - ~5000 3.5cm photons/bit

Canberra

- **4m, 70m antennas**

Daft Dust

System Architecture



Autonomous platform to demonstrate basic concepts

- Optical signal receiving
- Data processing
- Synchronous information transmission

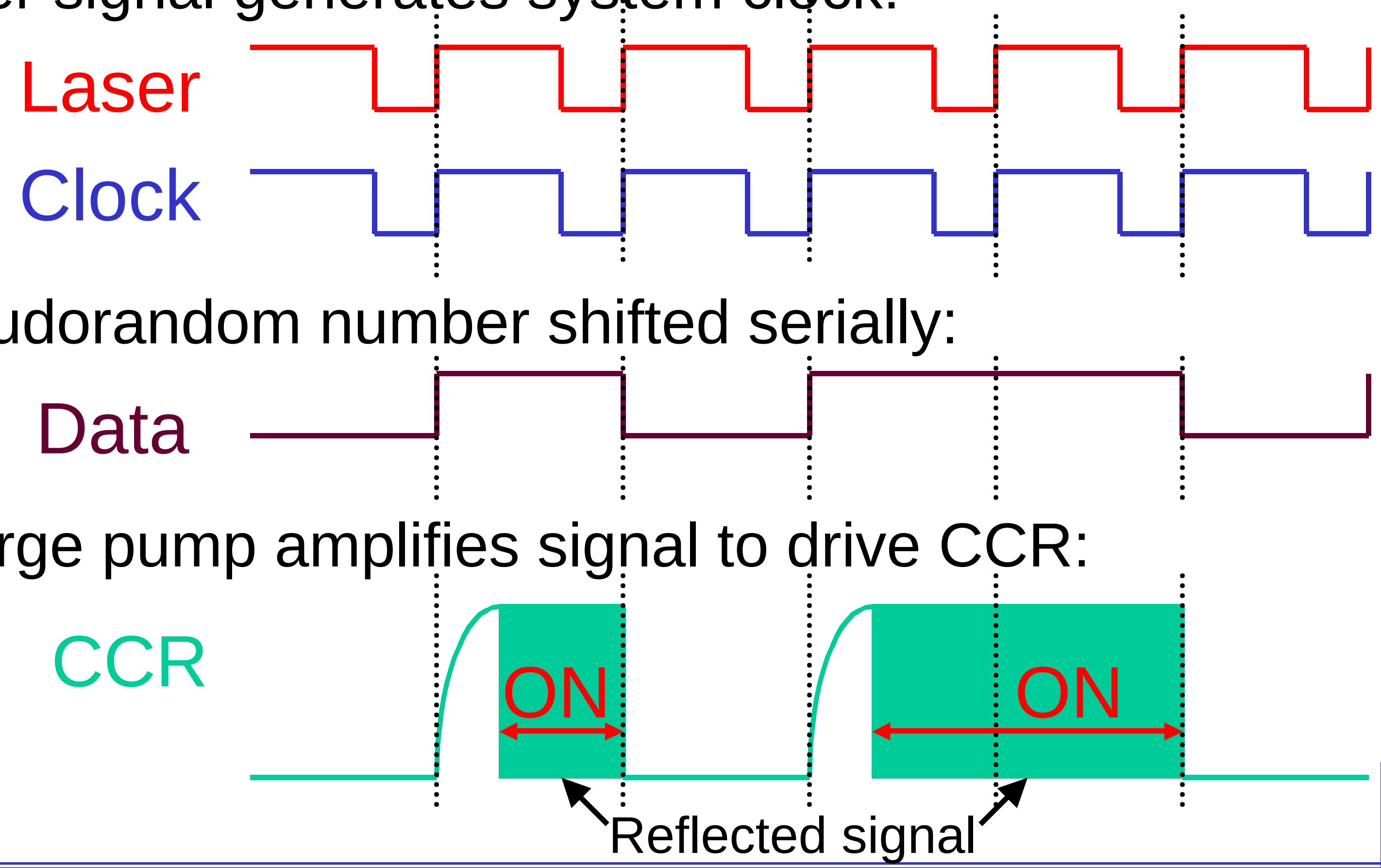
Daft Dust

Operation

Laser signal generates system clock:

Pseudorandom number shifted serially:

Charge pump amplifies signal to drive CCR:



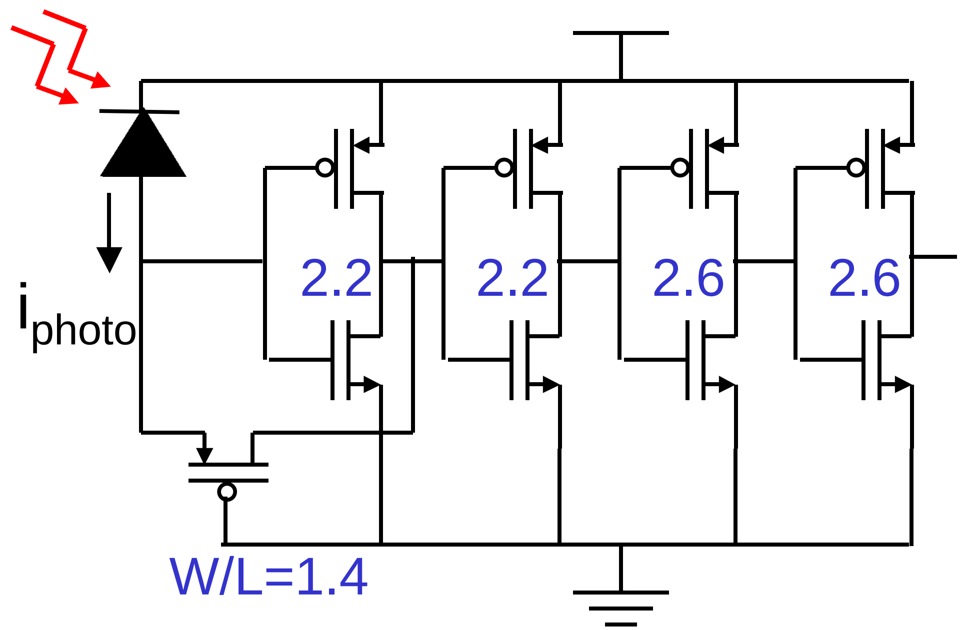
System Components

Optical Receiver

•Transimpedence amplifier with PMOS as feedback

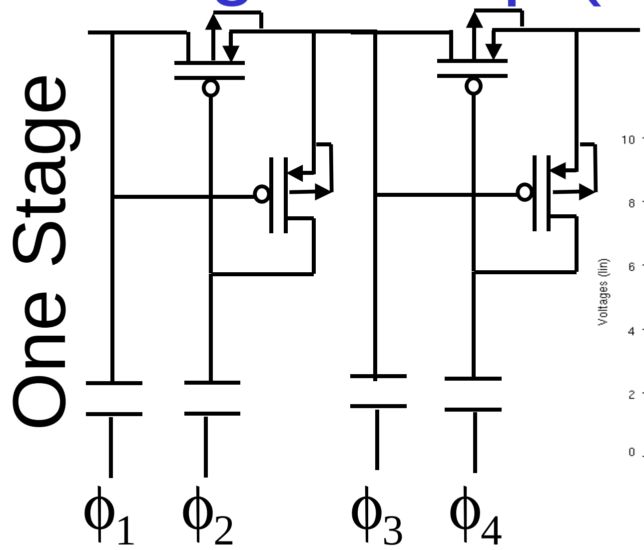
•Inverters as gain stages

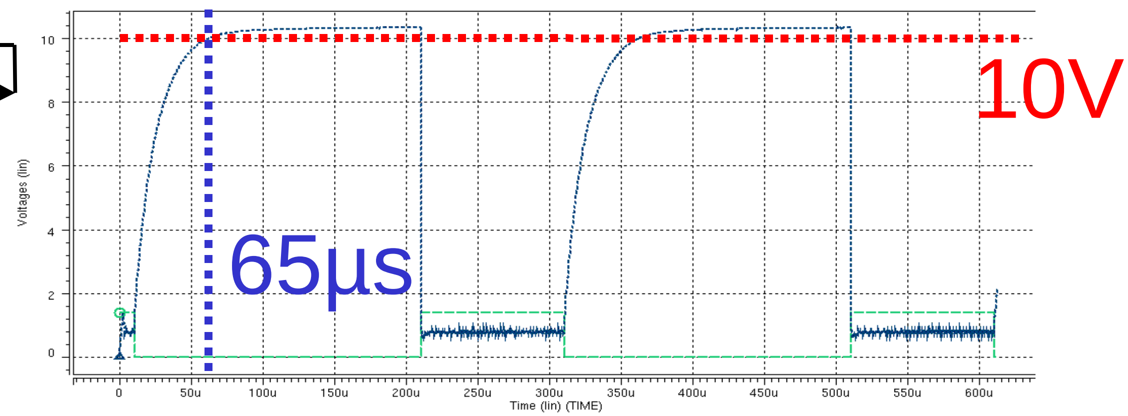
•Simulated avg. 4μW at 1kHz ⇒ 4nJ/bit



System Components

Charge Pump (Sawada, et al)





- PMOS transistors in separate wells
- 4 PMOS transistors per stage, 4 stages
- Increase potential by roughly 2Vdd per stage

System Components

LFSR/Shift Register - Standard Cell

- 8-bit linear feedback shift register (LFSR)
- 20-bit SR preset to 0101… training sequence
- Standard cell library
  - single phase pseudo-static logic style
  - targeted at 50-200MHZ
- 0.026 mm^2
- Measurements
  - 5.25nW at 1.4V, 1kbps $\Rightarrow$ 5.25pJ/bit
  - 440pA leakage at 1.4V
  - 1.19nW at 0.7V (V_t=0.55V), 1kbps $\Rightarrow$ 1.19pJ/bit

System Components

LFSR/Shift Register - Custom

- Ultra low-power design techniques
  - Static complementary CMOS logic style
  - Race-free asynchronous circuits
  - Branch-based layout
  - Minimum sized transistors
  - Minimize short circuit currents, and transistions
- 0.012 mm^2
- Simulated: 600pW at 1.4V, 1kbps
- Measured functional for Vdd < 0.5V

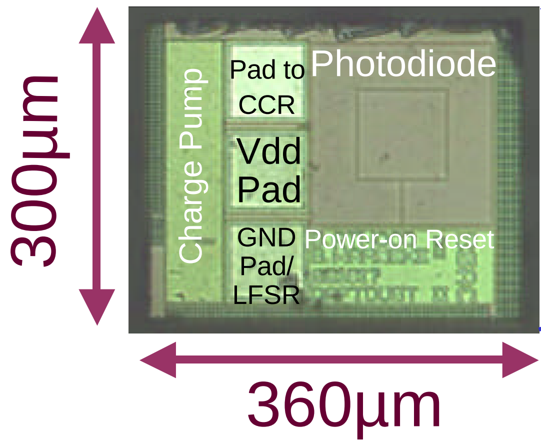
Simulation Results

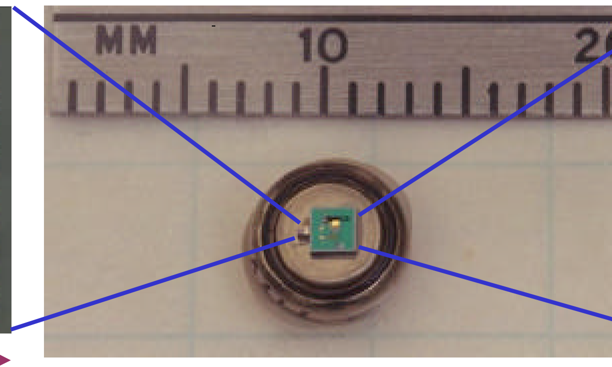
- Digital Circuits: 600pW (600fJ/bit)
- Optical Receiver: 4µW (4nJ/bit)
- Charge Pump: 12.5µW (12.5nJ/bit)
- Entire system: 17µW (17nJ/bit)

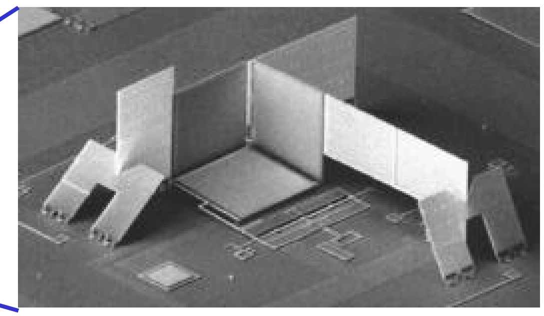
Power supply

- Zn-Air cell: 92 hours/mm^3
- Mg-Ti-Li rechargable cell: 3.3 hours/mm^3
- 0.7mm^2 solar cell (sunlight)

Daft Dust Device



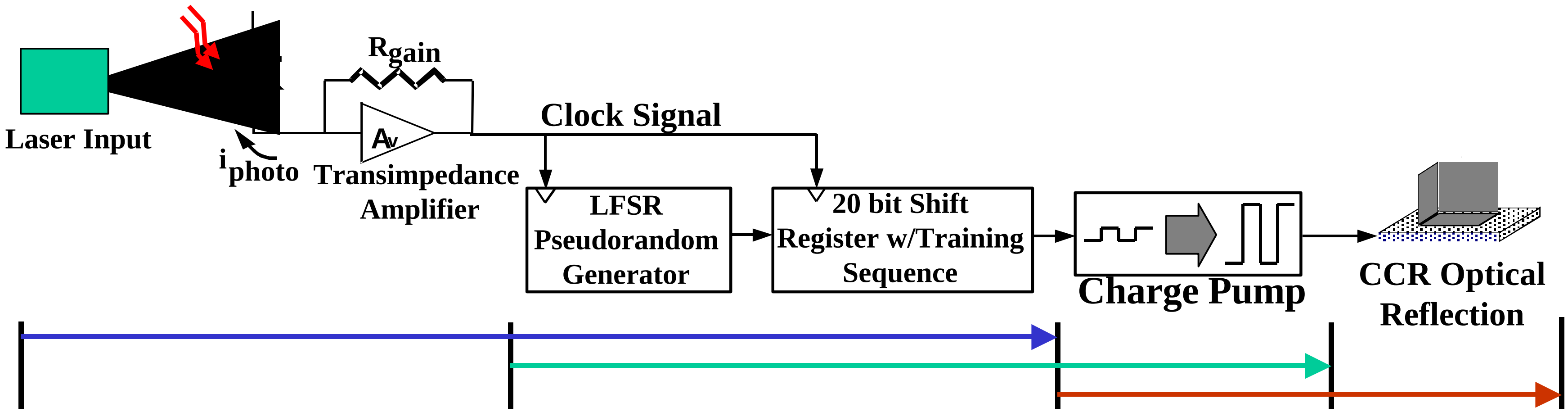




Courtesy of Victor Hsu

- 63 mm^3
- Circuits: 0.25 µm CMOS
  - digital circuits underneath ground pad
  - metal shields to prevent photogenerated carriers
- CCR: Cronos MUMPS

Demonstrated Functionality



- Laser to LFSR/SR output
- Receiver output to charge pump signal
- Charge pump driving CCR
- ~2 mm^2 solar cell power source

Future Work

- Thick-film batteries
- Integrated sensors
- Laser reprogrammable microprocessor
- Laser beam-steering

Conclusion

- Smart Dust Project
  - Autonomous sensing and communication
  - 1 mm^3
- Daft Dust
  - Preliminary Smart Dust mote
  - Micromachined CCR
  - 17µW, 63 mm^3